Association of
Montana Floodplain Managers

Design of Rock Riprap for Bank Stabilization

Wednesday March 7, 2012

Presented by:

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ALLIED ENGINEERING SERVICES, INC.

Diverse Projects • Solutions that Last

Applicability

- Lateral Migration Boundary
- Protection of In-Stream Structures
- Protection of Adjacent Infrastructure

Course Outline

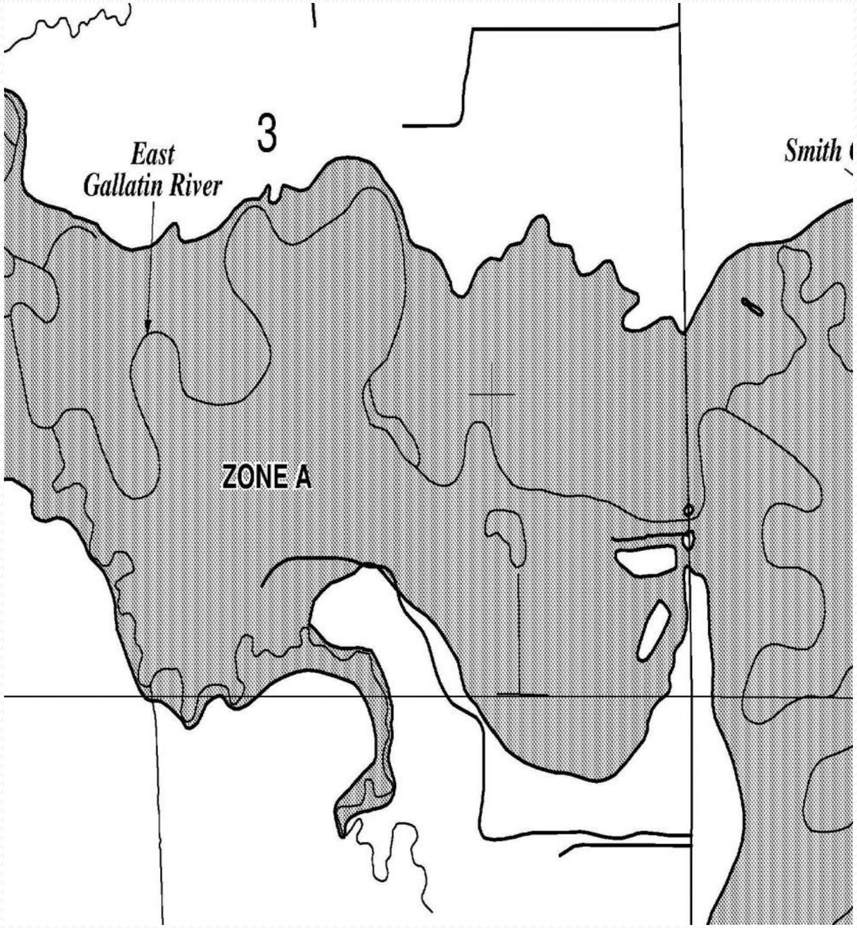
- Project Scoping
- Hydraulic Principles for Riprap Design
- Erosion Mechanisms & Failure Modes for Bank Riprap
- Determining Appropriate Rock Size
- Filter Layer Concepts
- Specifying Riprap Gradations & Thickness
- Other Design Considerations
- Basic Specifications for Riprap
- Application of Different Methods
- Example
- Questions and Answers

Project Scoping

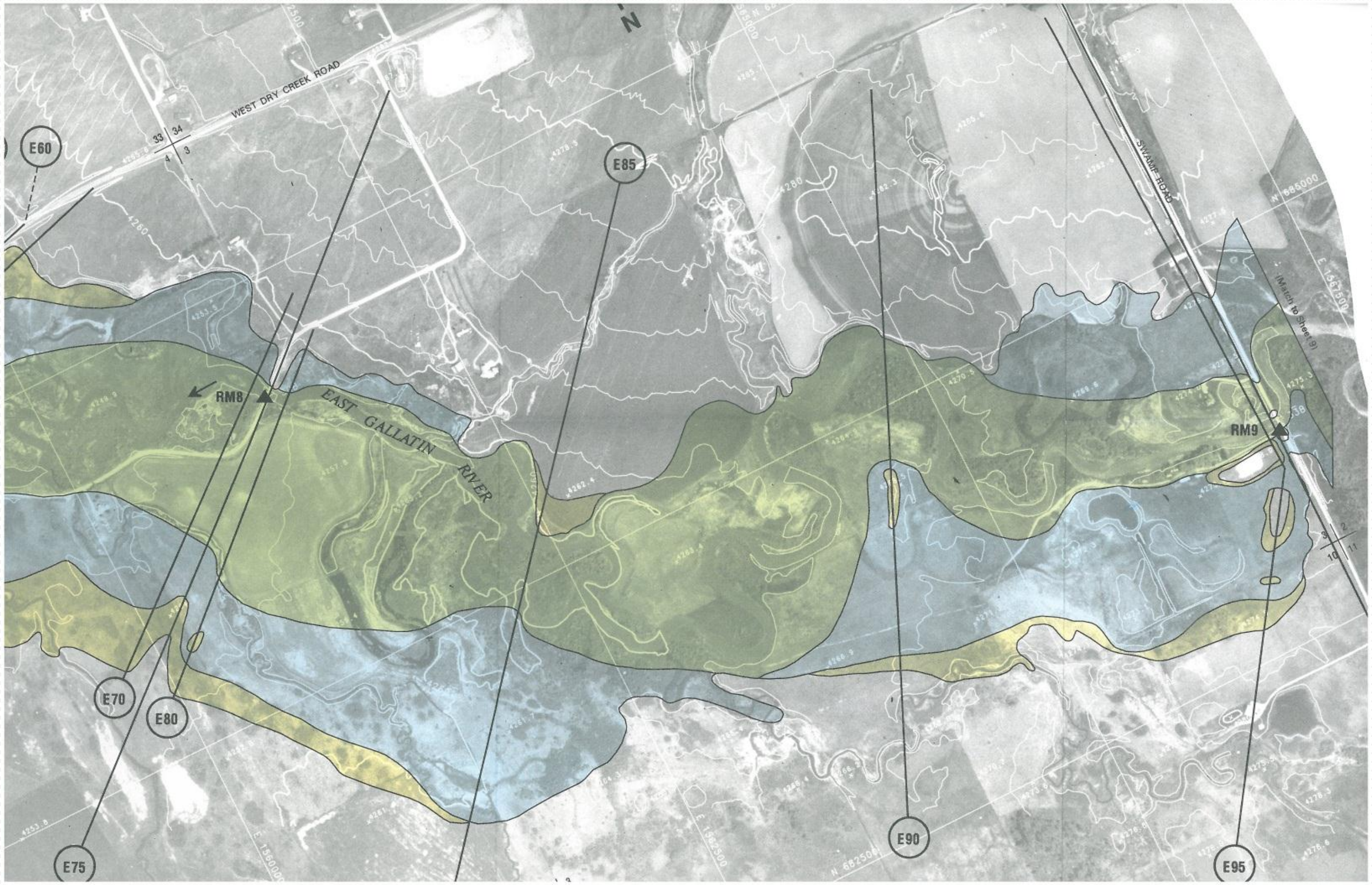
Project Scoping – Data Collection

- Gather & Review Existing Relevant Data
  - Flood Studies
  - Floodplain Maps
  - Hydrology
  - Topographic Data
- Site Reconnaissance
- Survey Data
  - Topography of Project Area
  - Cross-Sections
  - Horizontal & Vertical Datum

FEMA FIRM



NRCS Flood Study

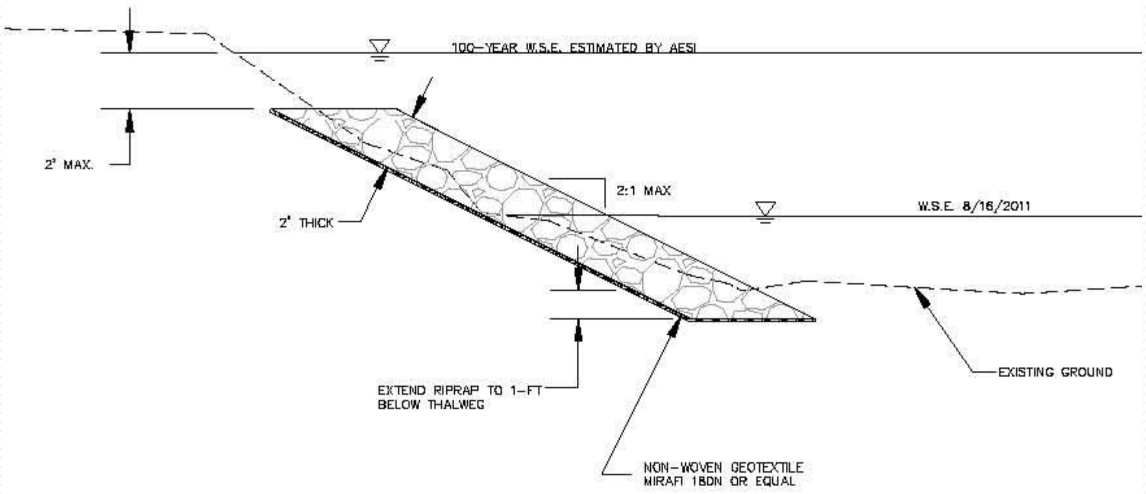


Project Scoping – Permitting

- http://dnrc.mt.gov/permits/streampermitting/default.asp#permits
- Floodplain Development Permit
- FEMA CLOMR/LOMR
- Clean Water Act (404)
- MT Natural Streambed & Land Preservation Act (310)
- MT Land Use License or Easement on Navigable Waters
- MT Short Term Water Quality

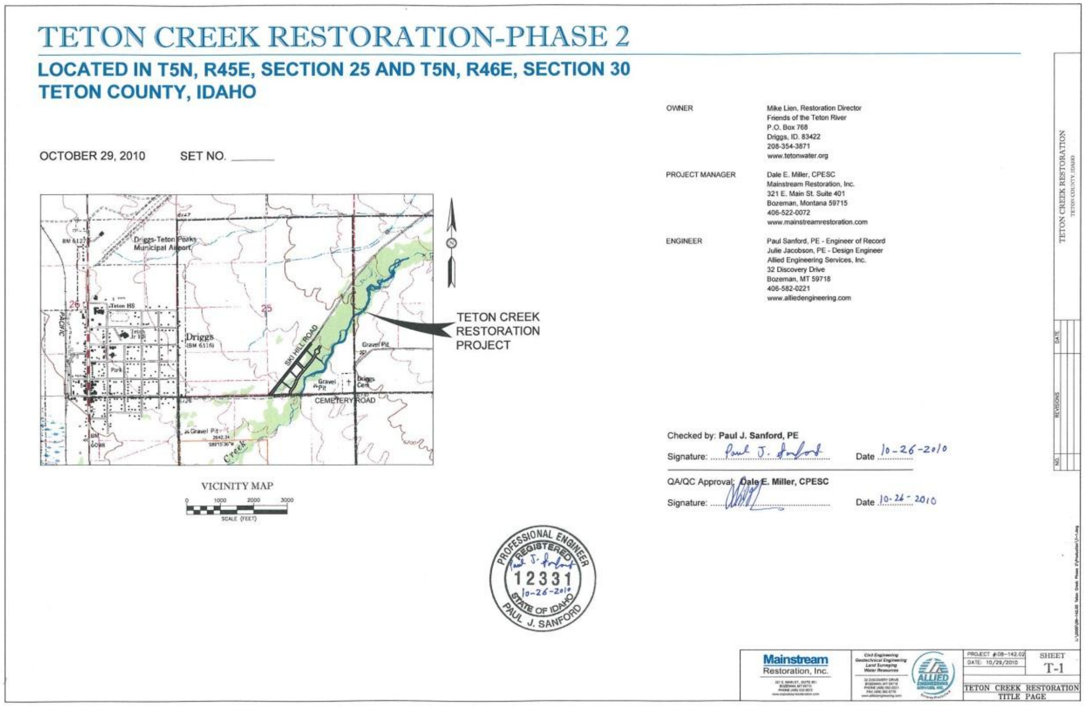
Project Scoping – Design

- Hydrology
- Hydraulics
  - Water Surface Profile Modeling
  - Scour
  - Shear Stress
- Rock Riprap Design



Project Scoping – Construction Documents

- Plans
- Specifications
- Bid Documents



Project Scoping – Construction Services

- Staking
- Inspection
- Certification

Hydraulic Principles for Riprap Design

Hydraulic Principles for Riprap Design

- Design Criteria – provide benchmarks by specifying quantifiable limits of performance
  - Infrastructure Protection
  - Channel Geometry
  - Vertical Stability
  - Lateral Stability

Hydraulic Principles for Riprap Design

- Hydrology
  - Design Discharge
    - Infrastructure – 1% Annual Chance Flood typical
  - Methods/Sources
    - Flood Insurance Study
    - USGS Gage Data
    - USGS Regression Equations
    - Rainfall Runoff (SCS Curve Number)

Hydraulic Principles for Riprap Design

- Hydraulics
  - Manning’s n
    - Handbook Method – calibrated photographs and other subjective methods
    - Analytical Methods – physically-based hydraulic roughness equations
    - Empirical – based on observation, experience, or experiment

Hydraulic Principles for Riprap Design

- Hydraulics (continued)
  - Tractive Force
    - "When water flows in a channel, a force is developed that acts in the direction of flow on the channel bed. This force, which is simply the pull of water on the wetted area, is known as the tractive force" (Chow, 1959)
    - T = γYS = 62.4 pcf x Depth in feet x Slope of Water Surface

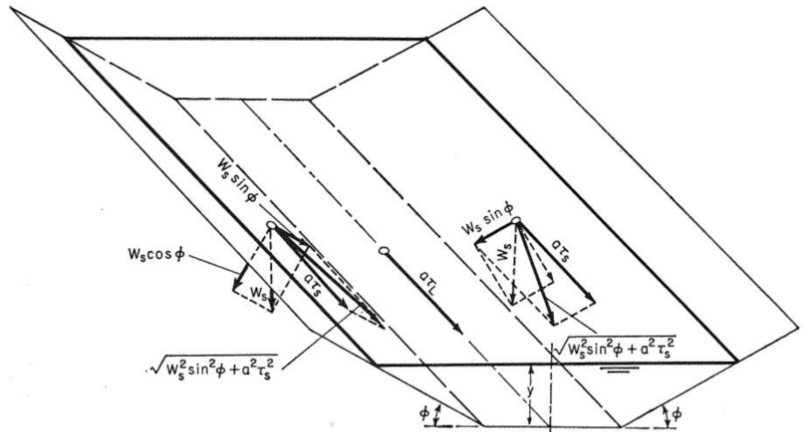


FIG. 7-8. Analysis of forces acting on a particle resting on the surface of a channel bed.

From Chow, 1959

Hydraulic Principles for Riprap Design

- Hydraulics (continued)
  - Scour
    - “The enlargement of a flow section by the removal of boundary material through the action of fluid motion during a single discharge event. The results of the scouring action may or may not be evident after the passing of the flood event” (Pemberton & Lara, 1984)
    - Numerous Methods to Estimate Scour Depth
      - e.g. Scour at Bridges
        - HEC-RAS
        - HEC No. 18

Erosion Mechanisms & Failure Modes for Bank Riprap

Erosion Mechanisms & Failure Modes for Bank Riprap

- Particle Erosion
- Translational Slide
- Modified Slump
- Slump

Erosion Mechanisms & Failure Modes for Bank Riprap

- Particle Erosion
  - Tractive force of flowing water exceed bank material's ability to resist movement
  - Initiated by abrasion, impingement of flowing water, eddy action, local flow acceleration, freeze/thaw action, ice, toe erosion
  - Causes:
    - Stone size not large enough
    - Individual stones removed by impact or abrasion
    - Side slope of the bank too steep

Erosion Mechanisms & Failure Modes for Bank Riprap

- Translational Slide
  - Downslope movement of a mass of stones with fault line on a horizontal plane
  - Initiated when channel bed scours and undermines toe of riprap blanket
  - Causes:
    - Bank side slopes too steep
    - Presence of excess hydrostatic pressure
    - Loss of foundation support at the toe of the riprap blanket caused by erosion of the lower part of the riprap blanket

Erosion Mechanisms & Failure Modes for Bank Riprap

- Modified Slump
  - Mass movement of material along an internal slip surface within the riprap blanket
  - Causes:
    - Bank side slopes too steep
    - Material critical to the support of upslope riprap is dislodged by settlement of the submerged riprap, impact, abrasion, particle erosion, or some other cause.

Erosion Mechanisms & Failure Modes for Bank Riprap

- Slump
  - Rotational-gravitational movement of material along a surface or rupture that has a concave upward curve
  - Cause-related to shear failure of the underlying base material that supports the riprap
  - Causes:
    - Non-homogeneous base material with layers of impermeable material that act as a fault line when subject to excess pore pressure
    - Side slope too steep and gravitational forces exceed the inertia forces of the riprap and base material along a friction plane

Determining Appropriate Rock Size

Determining Appropriate Rock Size

- Calculate Tractive Force
- Determine Permissible Tractive Force – maximum unit tractive force that will not cause serious erosion of the material forming the channel bed on a level surface
- If tractive force is greater than permissible tractive force, erosion occurs – use bigger rock
- Erosion Resistance
    - Depends on: stone shape, size, weight, and durability; riprap gradation and layer thickness; channel alignment, cross-section, gradient, and velocity distribution (USACE, 1994)

Determining Appropriate Rock Size

- Methods
  - Charts and Tables
  - Programs & Spreadsheets
    - E.g. Riprap Design System

Filter Layer Concepts

Filter Layer Concepts

- "A filter is a transitional layer of gravel, small stone, or fabric placed between the underlying soil and the structure." (HEC-11)
- The purpose of a filter
  - Prevents the migration of fine soil particles through voids
  - Distributes the weight of the armor units, causing more uniform settlement
  - Permits relief of hydrostatic pressures within the soils
  - For areas above water line, prevents surface water from causing erosion beneath the riprap

Filter Layer Concepts

- When should a filter be used?
  - Whenever the riprap is placed on fine grained material subject to significant subsurface drainage
- Proper design is critical to bank riprap stability
  - If filter openings are too large, excessive flow piping through the filter can cause erosion and failure of bank material below filter.
  - If filter openings are too small, the build-up of hydrostatic pressures behind the filter can cause a slip plane to form along the filter, causing a translational slide failure

Filter Layer Concepts

- Gradation of filter layer
  - Filtration Criteria
    - $D_{15filter}/D_{85soil}$ should be less than 5 to assure adequate filtration/retention
  - Permeability Criteria
    - $D_{15filter}/D_{15soil}$ should be above 5 to assure adequate permeability/drainage
  - Uniformity Criteria
    - $D_{15filter}/D_{15soil}$ should be less than 40 to assure adequate uniformity
    - $D_{50filter}/D_{50soil}$ should be less than 25 to assure adequate uniformity*

*additional retention/uniformity criteria for drainage filters by USBR & COE

Application of Different Methods

GRAIN SIZE DISTRIBUTION (ASTM D-422)

Project: Kerns Lake Dam Rehabilitation
Project Number: 09-019
Sample Identification: Import Gravel from Ranch Pit
Soil Classification: Sandy Gravel (GW) with Silt
Date Sampled: 04/24/09 by Bill Dabney
Date Tested: 6/6/09
Tested By: Doug Chandler

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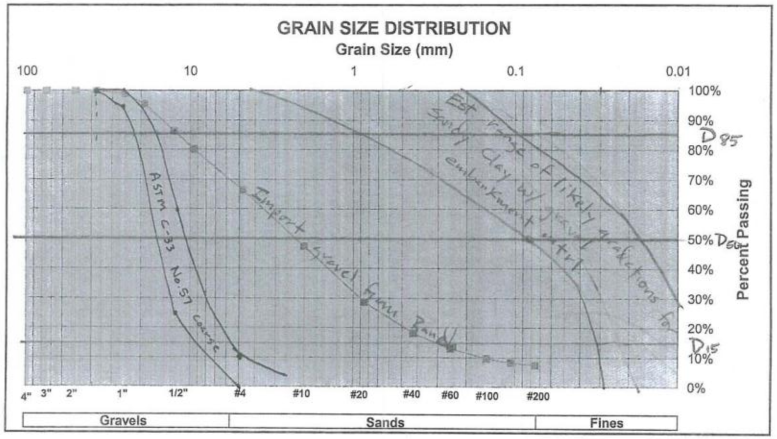
Summary of Lab Test Data

Natural Moisture Content:	0.0%
Gravel Portion (retained on #4 sieve):	33.7%
Sand Portion (passing # 4 & retained on #200 sieve):	58.8%
Fines Portion (passing #200 sieve):	7.5%



Sieve Size	Percent Passing
4"	100.0%
3"	100.0%
2"	100.0%
1.5"	100.0%
1"	98.9%
3/4"	95.4%
3/8"	80.1%
#4	66.3%
#10	47.4%
#20	28.7%
#40	18.0%
#60	13.0%
#100	9.7%
#140	8.3%
#200	7.5%

Reviewed By: ______

- Summary of Filter Design
  - $D_{15coarse}/D_{85fine} < 5 < D_{15coarse}/D_{15fine} < 40$

Filter Layer Concepts

- Other Filter Design Parameters
  - Filters should be clean – less than 5 to 10% fines
  - Ideally, gradation curves for riprap and filters should be parallel
- Thickness of Filter Layer
  - Single layer – 6 to 15 inches
  - Multiple layers – 4 to 8 inches (each individual layer)
  - Multiply by 1.5 for underwater placement
- Personal Opinion
  - Rather than multiple layers to transition between coarse riprap and fine grained bank – can often justify thicker layer (say 24”) of well-graded pit run sandy gravel with cobbles – some natural armoring of the outer layer occurs as fines wash away from uppermost layer under the riprap

Filter Layer Concepts

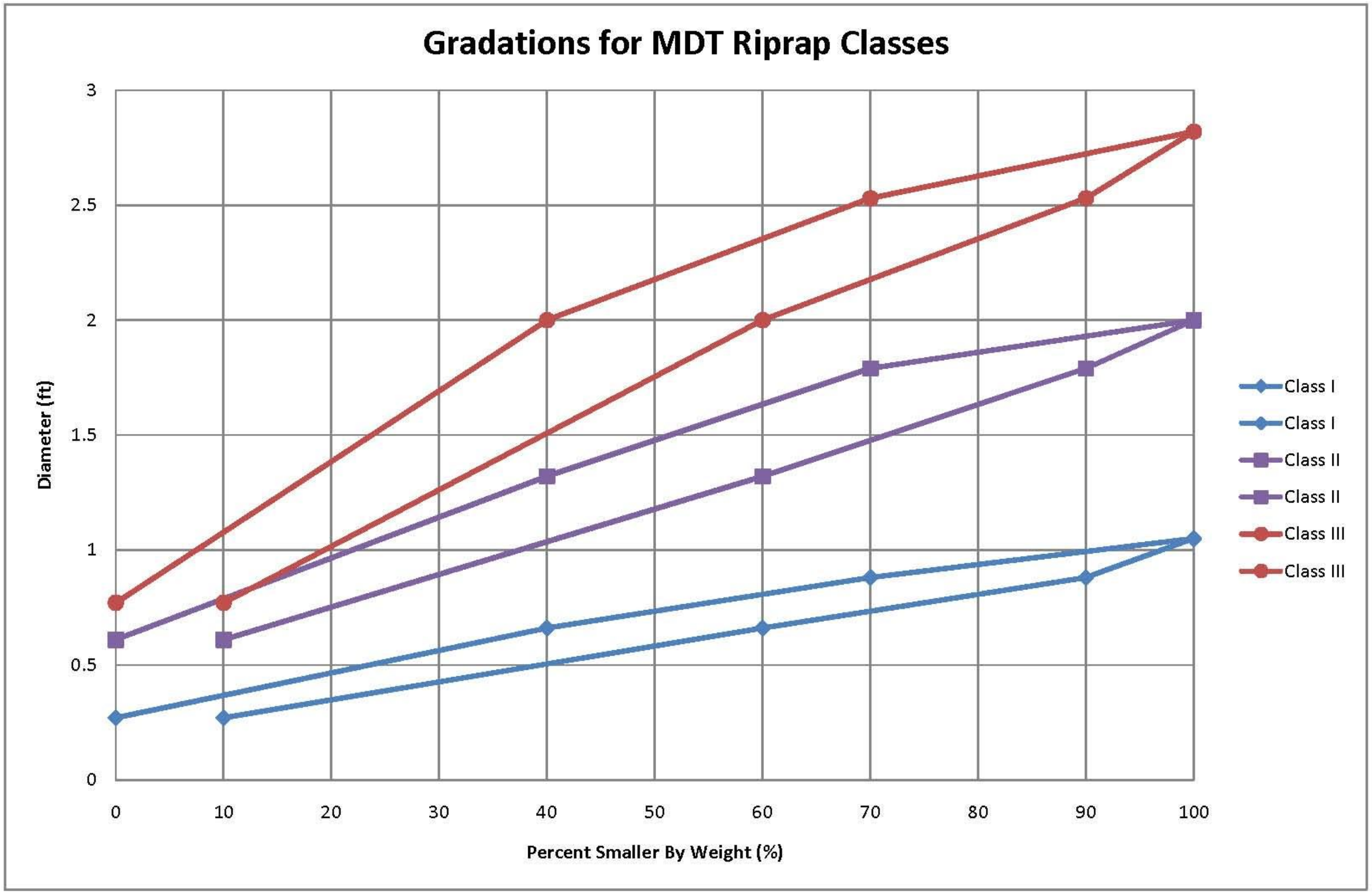
- Geotextile Filters
  - Cheaper
  - Acceptable for smaller riprap, especially with significant thickness of riprap layer
  - Vulnerable to tearing with large riprap – don’t drop rock
  - Not uniform support for protected soil on steep slopes – especially with large riprap (sometimes there is soil movement under the geotextile)
  - Difficult to impossible to place under water, especially if in current

Specifying Riprap Gradations & Thicknesses

Specifying Riprap Gradations & Thicknesses

- Specifying rock weight is alternative to gradation
- Three-point gradations are common
  - D_{100}, D_{50}, D_{15}
  - W_{100}, W_{50}, W_{15}

Specifying Riprap Gradations & Thicknesses



Specifying Riprap Gradations & Thicknesses

- USACE Gradations
  - USACE Gradations shown for rock with a unit weight equal to 155 pcf
  - Gradations shown below were developed for riprap placement in the dry, for low turbulence zones

D100 Max (in)	100% Lighter		50% Lighter		15% Lighter		D30 Min (ft)	D90 Min (ft)
	Max (lbs)	Min (lbs)	Max (lbs)	Min (lbs)	Max (lbs)	Min (lbs)		
12	81	32	24	16	12	5	0.48	0.70
15	159	63	47	32	23	10	0.61	0.88
18	274	110	81	55	41	17	0.73	1.06
21	435	174	129	87	64	27	0.85	1.23
24	649	260	192	130	96	41	0.97	1.40
27	924	370	274	185	137	58	1.10	1.59
30	1268	507	376	254	188	79	1.22	1.77
33	1688	675	500	338	250	105	1.34	1.94
36	2191	877	649	438	325	137	1.46	2.11
42	3480	1392	1031	696	516	217	1.70	2.47
48	5197	2078	1539	1039	769	325	1.95	2.82
54	7396	2958	2191	1479	1096	462	2.19	3.17

Specifying Riprap Gradations & Thicknesses

- FHWA Gradations
  - Assumes a specific gravity of 2.65
  - Based on AASHTO guidelines

Riprap Class	Rock Size (ft)	Rock Size (lbs)	% of Riprap Smaller Than
Facing	1.30	200	100
	0.95	75	50
	0.40	5	10
Light	1.80	500	100
	1.30	200	50
	0.40	5	10
1/4 Ton	2.25	1000	100
	1.80	500	50
	0.95	75	10
1/2 Ton	2.85	2000	100
	2.25	1000	50
	0.95	500	10
1 Ton	3.60	4000	100
	2.85	2000	50
	2.25	1000	10
2 Ton	4.50	8000	100
	3.60	4000	50
	2.85	2000	10

Specifying Riprap Gradations & Thicknesses

- Thickness Guidelines and Constraints
  - Normal range is 1.0 to 2.0 times D_{100}
  - Thickness greater than 1.0 may allow a reduction in stone size due to increased layer thickness
- HEC-11 Guidance
  - "All stones should be contained reasonably well within the riprap layer thickness"
    - Should not be less than D_{100} stone or less than 1.5 times D_{50} stone
    - Should not be less than 12 inches for practical placement
    - Should increase thickness by 50% for underwater placement
    - Should increase thickness by 6-12 inches where riprap will be subject to floating debris, ice, waves, wind, or bedforms

Other Design Considerations

Other Design Considerations

- Material Quality
  - Rock riprap preferred
  - Broken concrete and other rubble – must control material quality and gradation
  - Shape – neither the width or thickness of a stone should be less than 1/3 the length
  - Consider rock density – denser is better
  - In terms of stability, angular rock is better than rounded
- Edge Treatment
  - Toe – extend below scour depth
  - Flanks
  - Smooth hydraulic profile at edges is important
- Bank Slope – 2H:1V maximum

Other Design Considerations

- Placement
  - Hand and machine placing
    - Expensive
    - Allows for steeper side slopes
  - Dumping – segregation and breakage can occur
- Longitudinal Extent
  - Dependent on site conditions
  - HEC-11 provides some guidance

Other Design Considerations

- Design Height
  - Consider
    - Wave action for impinging flow
    - Design discharge and water level
    - Superelevation in bends
    - Hydraulic jumps
    - Freeboard desired
- Ice Damage
  - Crushing, impact loading, shearing forces
  - Potentially increase stability factor if location has historic ice problems

Basic Specifications for Riprap

Basic Specifications for Riprap

- Examples
  - Montana Department of Transportation Standard Specifications for Road and Bridge Construction, 2006 Edition.
  - Federal Highway Administration Hydraulic Engineering Circular No. 11 Design of Riprap Revetment, March 1989.

Basic Specifications for Riprap

- MDT Riprap Material Specifications
  - Furnish stone that is hard, durable, and angular in shape, resistant to weathering and water action, free from overburden, spoil, shale, structural defects, and organic material.
  - Each stone must have its greatest dimension not greater than three times its least dimension.
  - Do not use rounded stone or boulders from a streambed source as riprap. Do not use shale or stone with shale seams.

Basic Specifications for Riprap

- HEC-11 Riprap Material Specifications
  - Stone shall be hard, durable, angular in shape; resistant to weathering and water action; free from overburden, spoil, shale, and organic material.
  - Neither breadth nor thickness of a stone shall be less than one-third of its length.
  - Minimum unit weight shall be 155 lb/ft^3
  - LA Abrasion Test: no more than 40% loss

Application of Different Methods

Application of Different Methods

$$D_{30} = S_f C_s C_v C_t K_1 d \left(\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{0.5} \frac{V}{\sqrt{gd}} \right)^{2.5}$$

Where:

D_{30}	= stone size, feet
S_f	= Safety Factor (see description later in this section)
	= 1.25 downstream of concrete channels, end of dikes, flow impingement
C_s	= stability coefficient for incipient failure
	= 0.30 for angular rock = 0.375 for rounded rock
C_v	= vertical velocity distribution coefficient
	= 1.0 for straight channels, inside of bends
	= 1.283-0.2log(R/W), outside of bends (1 for R/W >26)
	(see Figure 2.5 for a description of R/W)
C_t	= thickness coefficient
	= 1.0 for thickness = $1D_{100}$(max) or $1.5D_{50}$(max), whichever is greater
d	= local depth of flow at same location as V, feet
g_s	= unit weight of stone, lbs/ft^3
g_w	= unit weight of water, lbs/ft^3
V	= local depth averaged velocity, V_{ss} for sideslope riprap, ft/s
g	= acceleration of gravity, ft/sec^2
K_1	= sideslope correction factor = 1 for bottom riprap
	= $1.25 - 1.811/m + 3.343/m^2$ for sideslope riprap,

where m denotes the number of horizontal units per one vertical unit (?H:1V) of the sideslope.

- USACE Method
  - For flow in man-made or natural channels having low turbulence and slopes less than 2%
  - Bed or Bank

Application of Different Methods

$$D_{50} = \left(\frac{6W}{\pi \gamma_s} \right)^{1/3}$$

Where:

$$W = \frac{0.000041 G_S V^6}{(G_S - 1)^3 \cos^3 \theta} \qquad \theta = \arctan(1/m)$$

D_{50}	=	stone size, ft
W	=	weight of stone, lbs
V	=	velocity, ft/s
g_s	=	unit weight of stone, lb/ft^3
g_w	=	unit weight of water, lb/ft^3
G_s	=	specific gravity of stone, (g_s / g_w)

- ASCE Method
  - Uses Isbash equation with a modification to account for channel bank slope.
  - Bed or Bank

Application of Different Methods

$$D_{50} = 0.0122 V_a^{2.06}$$

Where:

D_{50}	=	stone size, ft
V_a	=	average channel velocity, ft/s

- USBR Method
  - Developed for estimating riprap size downstream of a stilling basin
  - Procedure developed using eleven prototype installations with velocity varying from 1 fps to 18 fps.

Application of Different Methods

$$D_{50} = 0.01V_a^{2.44}$$

Where:

D_{50} = stone size, ft
V_a = average velocity in cross section, ft/s

- USGS Method
  - Equation resulted from field data taken from WA, OR, CA, NV, and AZ. Survey related hydraulic conditions to performance of riprap protection.
  - Surveys included 39 events of which 22 resulted in no riprap change. Of the 17 remaining events, 14 failures were caused by particle erosion.

Application of Different Methods

$$D_{50} = \frac{V_a^2}{2gC^2(G_s - 1)}$$

Where:

D_{50}	=	stone size, ft
V_a	=	average Channel Velocity, ft/s
G_s	=	specific gravity of stone (g_s/g_w)
g	=	acceleration of gravity, ft/s^2
C	=	0.86 for high turbulence zones
	=	1.20 for low turbulence zones

- Isbash Method
  - Developed for the construction of dams by depositing rock into running water.
  - Turbulence level (low or high) is factored into equation.

Application of Different Methods

$$W = \frac{0.00002\, V^6\, G_s}{(G_s - 1)^3 \sin^3(\rho - \theta)}$$

Where:

W	=	Theoretical minimum stable rock weight of outside stone to resist flow forces, lbs
V	=	stream velocity to which bank is exposed, ft/s
	=	4/3V_a for impinging flow
	=	2/3V_a for parallel flow
		V_a = average channel velocity, ft/s
D	=	70° for randomly placed rubble
2	=	bank angle, degrees
G_s	=	specific gravity of stone, (($_s$/ ($_w$)

- Cal B & SP Method
  - CA Dept. of Transportation developed this method to protect highway embankments.
  - Riprap embankments consist of one or more layers of rock.
  - Accounts for different types of flow (impinging or parallel) by modifying the average channel velocity

Application of Different Methods

- HEC-11 Method
  - Developed for use in rivers or streams with non-uniform flow conditions and discharges normally greater than 50 cfs.
  - Bed or Bank

Application of Different Methods

$$D_{50} = D_{50}' C_f C_s$$

Where:

$$D_{50}' = \frac{0.001 V_a^3}{\sqrt{d}\, K_1^{1.5}}$$

$$C_f = \left(\frac{safety \;\; factor}{1.2} \right)^{1.5}$$

$$K_1 = \left(1 \quad \begin{matrix} \sin^2 \theta \\ \sin^2 \phi \end{matrix} \right)^{0.5}$$

$$C_s = \frac{2.12}{(G_s - 1)^{1.5}}$$

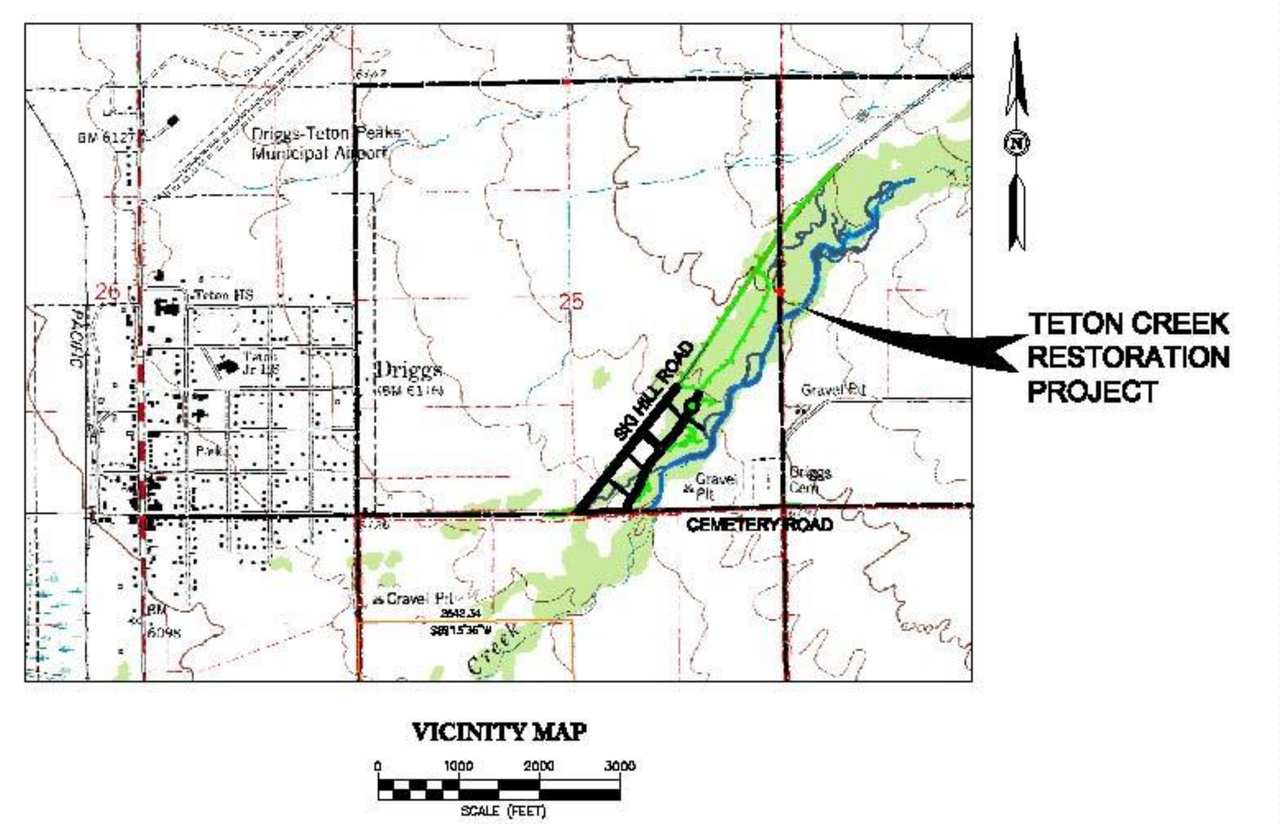
$$\theta = \arctan\left(\frac{1}{\text{Cotangent of sideslope}} \right)$$

D_{50}	=	stone size, ft
V_a	=	average channel velocity, ft/s
ϕ	=	material angle of repose, degrees
G_s	=	specific gravity of stone, (($_s$/ ($_w$)
d	=	average flow depth, ft

Examples

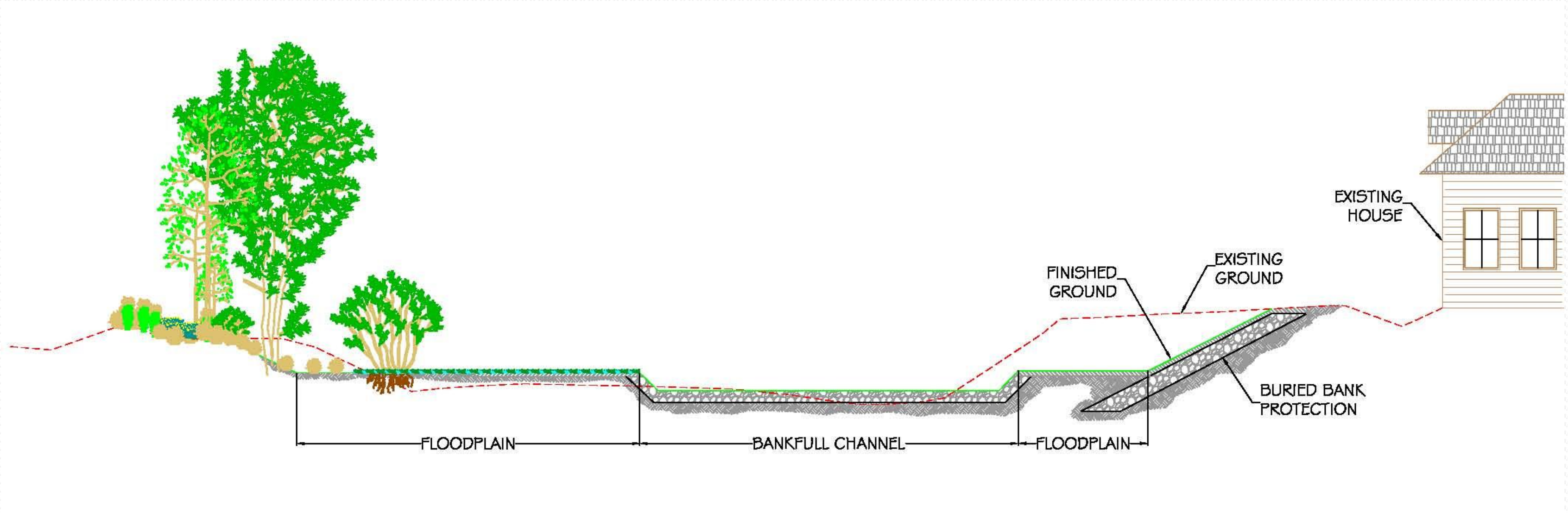
Examples – Teton Creek

- Teton Creek Stream Restoration
  - Located in Teton County, Idaho



2009 Aerial Image of Project Reach

Project Background:
Conceptual Cross-Section



Aerial View of Channelization

1960

2008

Why Was it Channelized?

1) To Control Floods???
2) To Fill in Wet Lands and Side Channels
3) Develop Infrastructure on Property

Phase 2 Construction: Fall 2010

Pre-Construction

Phase 2 Accomplishments:

1) Installed 2,700 linear feet of buried rock toe protection.

During Construction

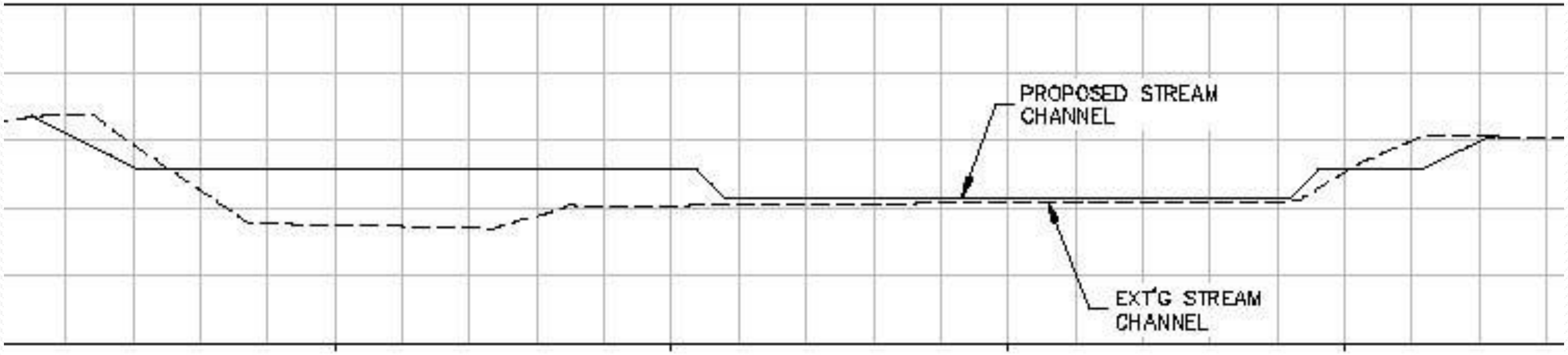
Phase 2 Construction: Fall 2010

Buried Rock Toe Protection – Slope Preparation – November 2010

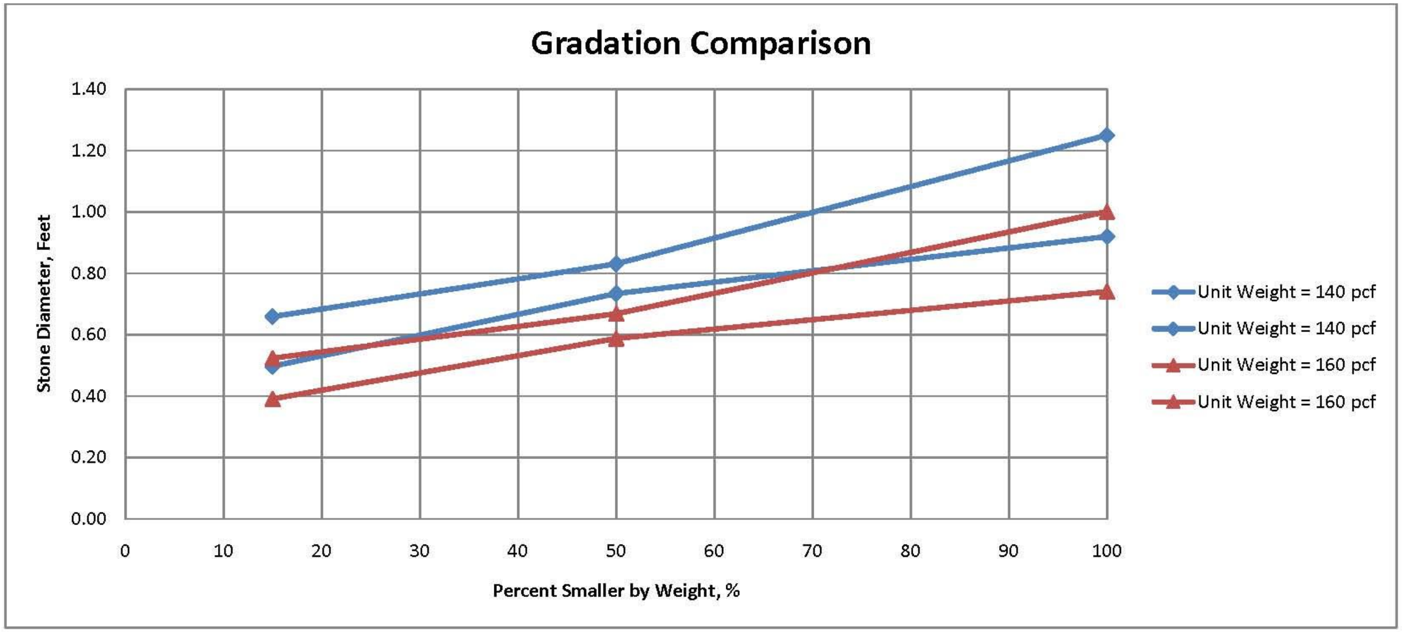
Runoff 2010

Examples – Teton Creek

- Teton Creek (continued)
  - Problem Input
    - Q_{100} = 2050 cfs
    - n = 0.053
    - Slope = 0.010 ft/ft
    - Channel & inset floodplain
    - Ch. btm width = 40 feet
    - Inset FP side slope = 2:1
- Riprap Design System
  - Size rock for buried bank protection at inset floodplain margin



Rock Riprap Gradation



- Teton Creek (cont.)
  - Riprap Design System
    - 160 pcf vs. 140 pcf riprap (USACE Method results shown)

Examples – Teton Creek

Alternative

As an alternative to the above Stone Mix A material specifications, rock from the River Rim source may be used. Stone will be hard and durable stone with less than 35 percent wear when tested for resistance to abrasion in conformance to ASTM C535. Bulk density will not be less than 140 pounds per dry cubic foot. The least dimension of any one piece will not be less than 1/3 the greatest dimension. Each load of Stone will be reasonably well graded from the smallest to the maximum size specified. Stone size gradation for this alternative stone will conform to the following gradation:

Percent Lighter by Weight	Stone Weight, lbs	
	Minimum	Maximum
100	99	247
50	49	73
15	15	37

* The size is measured along the B-Axis, which is the second largest dimension of the stone (i.e., use the dimensions of length, height, and width to describe the stone; with length being the A-Axis and the longest dimension of the stone, then the B-Axis is the longer of the height and width dimensions).

- Teton Creek (cont.)
  - Riprap Design System
    - Gradation & Material Specification for Stone with γ = 140 pcf

Questions and Answers

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